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Logitudinal Lepton Polarization Asymmetry in pure Leptonic B Decays

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Abstract

Longitudinal lepton polarization asymmetry in $B_q \to \ell^+ \ell^-$ ($q = d, s$ and $\ell = e, \mu, \tau$) decays is investigated. The analysis is done in a general manner by using the effective operators approach. It is shown that the longitudinal lepton polarization asymmetry would provide a direct search for the scalar and pseudoscalar type interactions, which are induced in all variants of Higgs-doublet models.

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It has been already pointed out by several authors [1, 2, 3] that the pure leptonic B decays $B_q \to \ell^+ \ell^-$ ($q = d, s$ and $\ell = e, \mu, \tau$) are very good probes to test new physics beyond the standard model (SM), mainly to reveal the Higgs sector. Those previous works were focused on the contributions induced by the scalar and pseudoscalar interactions realized in Higgs-doublets models. Within the SM, the decays are dominated by the $Z-$penguin and the box diagrams, which are helicity suppressed. We notice that Higgs-doublet models can generally enhance the branching ratio significantly. Also, as discussed in recent works, the decays are strongly correlated with the semi-leptonic B decays [3] and even with the muon anomalous magnetic moment [4]. Experimentally, it is expected that present and the forthcoming experiments on the $B-$physics ($B-$factories) can probe the flavor sector with high precision [5].

If we detect large discrepancy between the theoretical estimation of the decay branching fractions and the actually observed experimental results, then this could be either an evidence of new physics or of our lack of knowledge of the decay constants of B mesons, f_{B_q}. Therefore, the main interest would be a direct observation of new physics contributions belonging to the non-SM interactions, *i.e.* the scalar and pseudoscalar interactions, because within the SM the decay is through the axial vector interactions only. In this letter, we propose a new observable, namely the longitudinal lepton polarization asymmetry ($\mathcal{A}_{\rm LP}$). Though the measurement may be very difficult and challenging, we point out that this observable is very sensitive to those non-SM new interactions, and provides a direct evidence of their existence.

Taking into account all possible 4-fermi operators which could contribute to $B_q \to \ell^+ \ell^-$, these processes are governed by the following effective Hamiltonian [6],

$$\begin{aligned} \mathcal{H}_{\rm eff} &= -\frac{G_F \alpha}{2\sqrt{2}\pi} \left(V_{tq}^* V_{tb} \right) \Big\{ \mathcal{C}_{\rm AA} (\bar{q}\, \gamma_\mu \gamma_5\, b)(\bar{\ell}\, \gamma^\mu \gamma_5\, \ell) \\ &\quad + \mathcal{C}_{\rm PS} (\bar{q}\, \gamma_5\, b)(\bar{\ell}\, \ell) + \mathcal{C}_{\rm PP} (\bar{q}\, \gamma_5\, b)(\bar{\ell}\, \gamma_5\, \ell) \Big\} \ , \end{aligned} \tag{1}$$

by normalizing all terms with the overall factors of the SM. In particular, within the SM one has $\mathcal{C}_{\rm PS}^{\rm SM} = \mathcal{C}_{\rm PP}^{\rm SM} \simeq 0$ and $\mathcal{C}_{\rm AA}^{\rm SM} = Y(x_{tW})/\sin^2\theta_W$, where $Y(x_{tW})$ is the Inami-Lim function [7] with $x_{tW} = (m_t/M_W)^2$. The contributions proportional to $m_{d,s}$ are neglected, and the neutral Higgs contributions in $\mathcal{C}_{\rm PS}^{\rm SM}$ and $\mathcal{C}_{\rm PP}^{\rm SM}$ are proportional to ${m_b}^2/{m_W}^2$, and therefore also neglected.

After using the PCAC ansatz to derive the relation between the operators, the most general matrix element for the decay is

$$\mathcal{M} = i f_{B_q} \frac{G_F \alpha}{2\sqrt{2}\pi} V_{tq}^* V_{tb} \left[\left(2 m_\ell \mathcal{C}_{\rm AA} - \frac{m_{B_q}^2}{m_b + m_q} \mathcal{C}_{\rm PP} \right) \bar{\ell}\, \gamma_5\, \ell - \frac{m_{B_q}^2}{m_b + m_q} \mathcal{C}_{\rm PS} \bar{\ell}\, \ell \right] . \tag{2}$$

Using Eq. (2), the branching ratio for $B_q \to \ell^+ \ell^-$ becomes

$$\begin{aligned} \mathcal{B}(B_q \to \ell^+ \ell^-) &= \frac{G_F^2\, \alpha^2}{64\pi^3} \left| V_{tq}^* V_{tb} \right|^2 \tau_{B_q} f_{B_q}^2\, m_{B_q} \sqrt{1 - \frac{4 m_\ell^2}{m_{B_q}^2}} \\ &\quad \times \left[\left| 2 m_\ell\, \mathcal{C}_{\rm AA} - \frac{m_{B_q}^2}{m_b + m_q} \mathcal{C}_{\rm PP} \right|^2 + \left(1 - \frac{4 m_\ell^2}{m_{B_q}^2} \right) \left| \frac{m_{B_q}^2}{m_b + m_q} \mathcal{C}_{\rm PS} \right|^2 \right] , \end{aligned} \tag{3}$$

where τ_{B_q} is the life-time of B_q meson. The QCD correction in this decay mode is remarkably negligible. As can be seen easily, the significant branching ratio within the SM could be expected only for $\ell = \tau, \mu$ due to the lepton mass dependence.

We now define an observable using the lepton polarization. Since in the dilepton rest frame we can define only one direction, the lepton polarization vectors in each lepton's rest frame are defined as

$$\bar{s}^{\mu}_{\ell^{\pm}} = \left(0, \pm\frac{\mathrm{p}_-}{|\mathrm{p}_-|}\right) , \tag{4}$$

and in the dilepton rest frame they are boosted to

$$s^{\mu}_{\ell^{\pm}} = \left(\frac{|\mathrm{p}_-|}{m_\ell}, \pm\frac{E_\ell \mathrm{p}_-}{m_\ell|\mathrm{p}_-|}\right) , \tag{5}$$

where E_ℓ is the lepton energy. Finally the longitudinal lepton polarization asymmetry in $B_q \to \ell^+ \ell^-$ is defined as follows;

$$\mathcal{A}^{\pm}_{\rm LP} \equiv \frac{[\Gamma(s_{\ell^-}, s_{\ell^+}) + \Gamma(\mp s_{\ell^-}, \pm s_{\ell^+})] - [\Gamma(\pm s_{\ell^-}, \mp s_{\ell^+}) + \Gamma(-s_{\ell^-}, -s_{\ell^+})]}{[\Gamma(s_{\ell^-}, s_{\ell^+}) + \Gamma(\mp s_{\ell^-}, \pm s_{\ell^+})] + [\Gamma(\pm s_{\ell^-}, \mp s_{\ell^+}) + \Gamma(-s_{\ell^-}, -s_{\ell^+})]} , \tag{6}$$

and it becomes

$$\mathcal{A}_{\rm LP}(B_q \to \ell^+ \ell^-) = \frac{2\sqrt{1-\frac{4m_\ell^2}{m_{B_q}^2}} Re\left[\frac{m_{B_q}^2}{m_b+m_q}\mathcal{C}_{\rm PS}\left(2m_\ell \mathcal{C}_{\rm AA} - \frac{m_{B_q}^2}{m_b+m_q}\,\mathcal{C}_{\rm PP}\right)\right]}{\left|2m_\ell\mathcal{C}_{\rm AA} - \frac{m_B^2}{m_b+m_q}\mathcal{C}_{\rm PP}\right|^2 + (1-\frac{4m_\ell^2}{m_{B_q}^2})\left|\frac{m_{B_q}^2}{m_b+m_q}\mathcal{C}_{\rm PS}\right|^2}, \tag{7}$$

with $\mathcal{A}^{+}_{\rm LP} = \mathcal{A}^{-}_{\rm LP} \equiv \mathcal{A}_{\rm LP}$. It is clear that within the SM $\mathcal{A}_{\rm LP}(B_q \to \ell^+ \ell^-) \simeq 0$, and becomes non-zero if and only if $\mathcal{C}_{\rm PS} \neq 0$. Therefore, this observable would be the best probe to search for new physics induced by the pseudoscalar type interactions. We also remark that the dependence on the flavor of the valence quark in $\mathcal{A}_{\rm LP}(B_q \to \ell^+ \ell^-)$ is tiny, therefore the longitudinal lepton polarization asymmetry is almost the same for $q = d$ or $q = s$.

Before considering physics beyond the SM, let us briefly review the SM predictions for the processes. For consistency, the top mass is rescaled from its pole mass, $m_t = 175 \pm 5$ GeV, to the $\overline{\rm MS}-$mass, $m_t(\overline{\rm MS}) = 167 \pm 5$ GeV. For numerical calculations throughout the paper, we use the world–averaged values for all other parameters [8], *i.e.* :

$m_{B_q^0} = 5279.2 \pm 1.8$ MeV, $m_W = 80.41 \pm 0.10$ GeV, $\tau_{B_q^0} = 1.56 \pm 0.04\ ({\rm ps})^{-1}$, $m_e = 0.5$ MeV, $m_\mu = 105.7$ MeV, $m_\tau = 1777$ MeV, $\sin^2\theta_W(\overline{\rm MS}) = 0.231$, $\alpha = 1/129$, $f_{B_d} = 210 \pm 30$ MeV and $f_{B_s} = 245 \pm 30$ MeV [9].

Within the SM and by using the experimental bounds on the Wolfenstein parametrization $(A, \lambda) = (0.819 \pm 0.035, 0.2196 \pm 0.0023)$ together with the unitarity of CKM matrix [8, 10], we get

$$\begin{aligned} |V_{ts}| &\approx A\,\lambda^2 = 0.0395 \pm 0.0019\,, \\ |V_{td}| &\approx A\,\lambda^3\sqrt{(1-\rho)^2+\eta^2} = 0.004 \sim 0.013\,. \end{aligned} \tag{8}$$

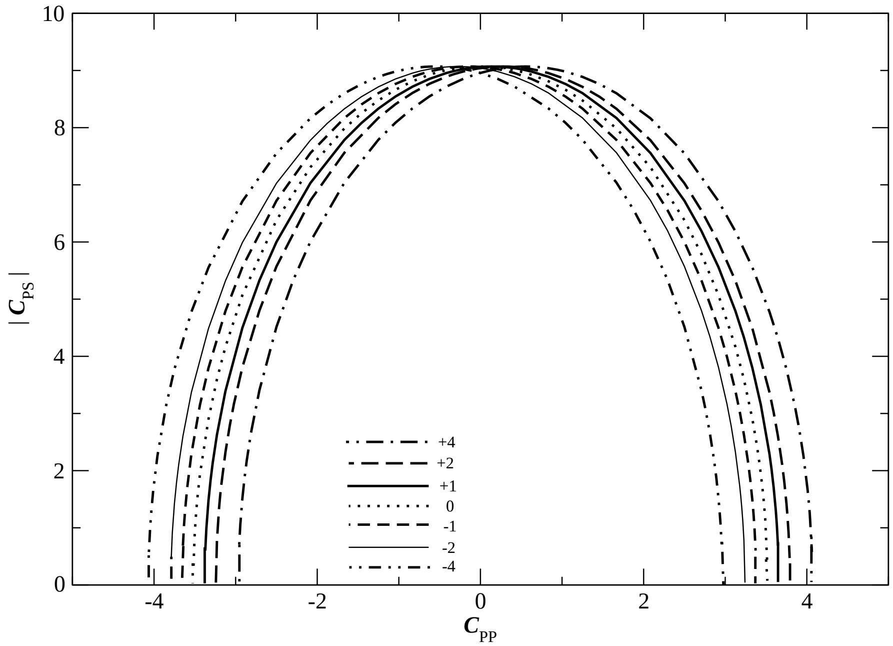

Figure 1: The upper bounds for $\mathcal{C}_{\rm PP}$ vs $|\mathcal{C}_{\rm PS}|$ for $\mathcal{C}_{\rm AA} = (-4, -2, -1, 0, +1, +2, +4) \times \mathcal{C}_{\rm AA}^{\rm SM}$ using the experimental bound on $\mathcal{B}(B_s \to \mu^+ \mu^-)$.

Adopting the next-to-leading order result for $Y(x_{t_W})$ [11], and using the central values for all input parameters, lead to the following SM predictions,

$$\mathcal{B}(B_d \to \ell^+ \ell^-) = \begin{cases} 3.4 \times 10^{-15} \left(\frac{f_{B_d}}{210 \ MeV}\right)^2 & , \quad \ell = e \\ 1.5 \times 10^{-10} \left(\frac{f_{B_d}}{210 \ MeV}\right)^2 & , \quad \ell = \mu \\ 3.2 \times 10^{-8} \left(\frac{f_{B_d}}{210 \ MeV}\right)^2 & , \quad \ell = \tau \end{cases} , \tag{9}$$

$$\mathcal{B}(B_s \to \ell^+ \ell^-) = \begin{cases} 8.9 \times 10^{-14} \left(\frac{f_{B_s}}{245 \ MeV}\right)^2 & , \quad \ell = e \\ 4.0 \times 10^{-9} \left(\frac{f_{B_s}}{245 \ MeV}\right)^2 & , \quad \ell = \mu \\ 8.3 \times 10^{-7} \left(\frac{f_{B_s}}{245 \ MeV}\right)^2 & , \quad \ell = \tau \end{cases} . \tag{10}$$

These predictions should be confronted with the present experimentally known bounds of $\mathcal{B}(B_q \to \ell^+ \ell^-)$ at 95% CL [12],

$$\mathcal{B}(B_d \to \mu^+ \mu^-) < 8.6 \times 10^{-7} , \tag{11}$$

$$\mathcal{B}(B_s \to \mu^+ \mu^-) < 2.6 \times 10^{-6} . \tag{12}$$

To analyze the decay processes and simulataneously find the possible new physics signal, we first employ the experimental bound of the branching ratio which constraints the coefficients ($\mathcal{C}$'s) more strictly after comparing the theoretical predictions with the known experimental bounds, *i.e.* $\mathcal{B}(B_s \to \mu^+ \mu^-)$ (see Eqs. (9)$\sim$(12)), and obtain the allowed region on the $\mathcal{C}_{\rm PS} - \mathcal{C}_{\rm PP}$ parameter space for various values of $\mathcal{C}_{\rm AA}$. This is shown in Fig. 1. Furthermore, suppose that the branching ratio is measured first, then it must

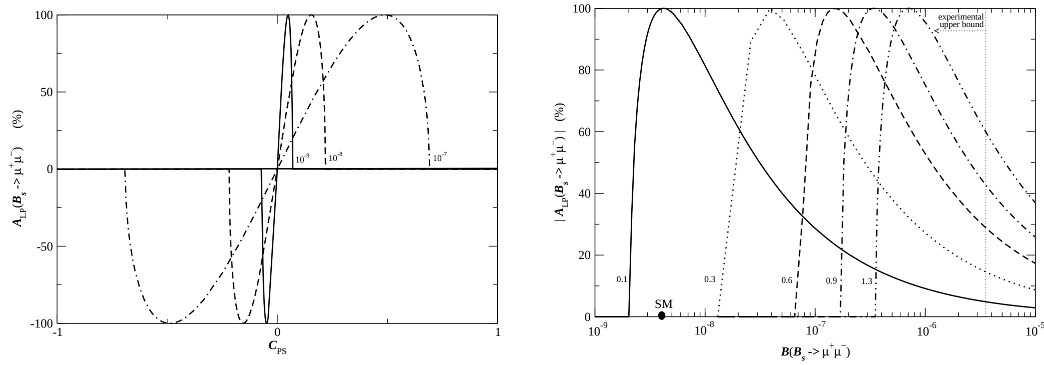

Figure 2: The correlation between $\mathcal{A}_{\rm LP}(B_s \to \mu^+\mu^-)$ and $\mathcal{C}_{\rm PS}$ for various $\mathcal{B}(B_s \to \mu^+\mu^-) = 10^{-7}, 10^{-8}, 10^{-9}$ (left), and the correlation between $\mathcal{A}_{\rm LP}(B_s \to \mu^+\mu^-)$ and $\mathcal{B}(B_s \to \mu^+\mu^-)$ for various $\mathcal{C}_{\rm PS} = 0.1, 0.3, 0.6, 0.9, 1.3$ (right).

be worth to show a general correlation between the branching ratio and the longitudinal lepton polarization asymmetry represented by the following equation,

$$\begin{aligned}
\mathcal{A}_{\rm LP}(B_q \to \ell^+\ell^-) &= \pm \frac{2a_q\sqrt{1-\frac{4m_\ell^2}{m_{B_q}^2}}}{\mathcal{B}(B_q \to \ell^+\ell^-)}\, Re\left[\frac{m_{B_q}^2}{m_b+m_q}\mathcal{C}_{\rm PS}\right. \\
&\quad \left.\times\sqrt{\frac{\mathcal{B}(B_q \to \ell^+\ell^-)}{a_q} - \left(1-\frac{4m_\ell^2}{m_{B_q}^2}\right)\left|\frac{m_{B_q}^2}{m_b+m_q}\mathcal{C}_{\rm PS}\right|^2}\,\right], \qquad (13)
\end{aligned}$$

by eliminating $\mathcal{C}_{\rm AA}$ and $\mathcal{C}_{\rm PP}$ in Eqs. (3) and (7), where the constant a_q is defined as

$$a_q \equiv \frac{G_F^2\alpha^2}{64\pi^3}\left|V_{tq}^* V_{tb}\right|^2 \tau_{B_q} f_{B_q}^2 m_{B_q}\sqrt{1-\frac{4m_\ell^2}{m_{B_q}^2}}\,. \qquad (14)$$

This is depicted in Fig. 2. The left-hand-side figure shows a correlation between $\mathcal{A}_{\rm LP}(B_s \to \mu^+\mu^-)$ and $\mathcal{C}_{\rm PS}$ for various $\mathcal{B}(B_s \to \mu^+\mu^-)$, while the right-hand-side one is between $\mathcal{A}_{\rm LP}(B_s \to \mu^+\mu^-)$ and $\mathcal{B}(B_s \to \mu^+\mu^-)$ for various $\mathcal{C}_{\rm PS}$.

As a real example for the case in which $\mathcal{C}_{\rm PS}$ is non-zero, we adopt the type II 2-Higgs-doublet models (2HDM-II). In this model

$$\mathcal{C}_{\rm AA}^{\rm 2HDM-II} = \mathcal{C}_{\rm AA}^{\rm SM},$$

while

$$\mathcal{C}_{\rm PS}^{\rm 2HDM-II} = \mathcal{C}_{\rm PP}^{\rm 2HDM-II} = \frac{m_\ell(m_b+m_q)}{4M_W^2\sin^2\theta_W}\tan^2\beta\frac{\ln x_{H^\pm t}}{x_{H^\pm t}-1}\,, \qquad (15)$$

at large $\tan\beta$ limit [2], and $x_{H^\pm t} = (m_{H^\pm}/m_t)^2$. Some particular cases in the right-hand-side figure of Fig. 2 can be realized by, for instance,

> $(m_{H^\pm}, \tan\beta) = (200\,{\rm GeV}, 40)$ for $\mathcal{C}_{\rm PS} = 0.1$, $(200\,{\rm GeV}, 70)$ for $\mathcal{C}_{\rm PS} = 0.3$, $(200\,{\rm GeV}, 95)$ for $\mathcal{C}_{\rm PS} = 0.6$, $(200\,{\rm GeV}, 120)$ for $\mathcal{C}_{\rm PS} = 0.9$, $(200\,{\rm GeV}, 145)$ for $\mathcal{C}_{\rm PS} = 1.3$.

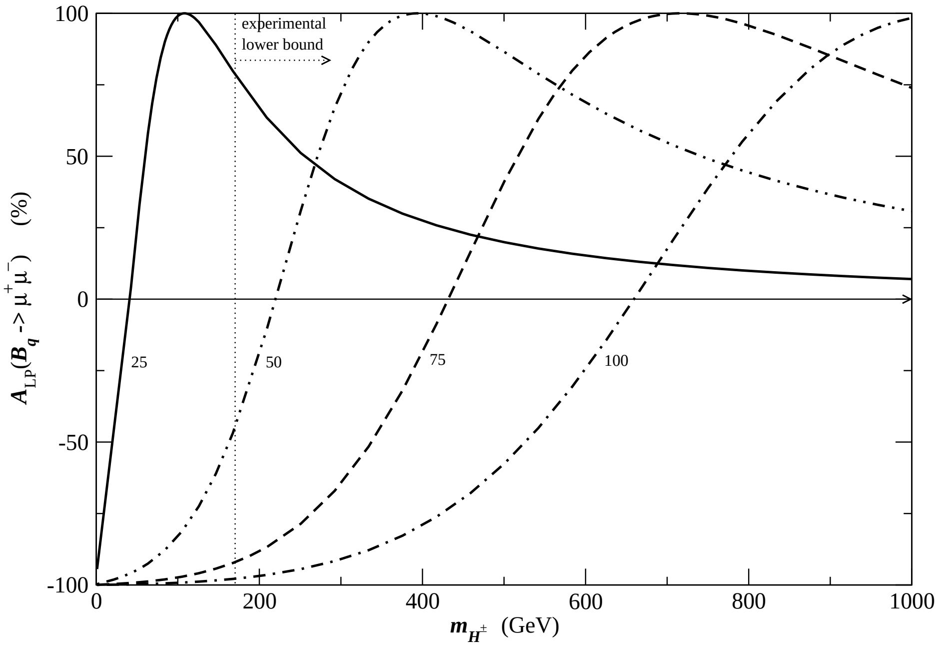

Figure 3: The longitudinal lepton polarization $\mathcal{A}_{\rm LP}(B_q \to \mu^+\,\mu^-)$ as a function of $m_{H^\pm}$ for various $\tan\beta = 25, 50, 75, 100$.

Finally, in Fig. 3 we show the dependences of $\mathcal{A}_{\rm LP}(B_q \to \mu^+\,\mu^-)$ on $m_{H^\pm}$ and $\tan\beta$.

In conclusion we have considered a general analysis exploring the longitudinal lepton polarization asymmetry in the $B_q \to \ell^+\,\ell^-$ decays. We have shown that this observable would provide a direct measurement of the physics of scalar and pseudoscalar type interactions. We also note that more information about these new interactions can be obtained by combining the present analysis with the other observables from $B \to X_q\ell^+\ell^-$ [13].

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References

[1] K. S. Babu and C. Kolda, *Phys. Rev. Lett.* **84** (2000) 228.

[2] H. E. Logan and U. Nierste, *Nucl. Phys.* **B586** (2000) 39.

[3] C. Bobeth, T. Ewerth, F. Krüger and J. Urban, *Phys. Rev.* **D64** (2001) 074014.

[4] A. Dedes, H. K. Dreiner and U. Nierste, hep-ph/0108037 (2001).

[5] D. Boutigny *et.al.* (BaBar Collaboration), *SLAC-R-0457* (1995) ;
M. T. Cheng *et.al.* (Belle Collaboration), *BELLE-TDR-3-95* (1995) ;
P. Krizan *et.al.* (HERA-B Collaboration), *Nucl. Inst. Meth.* **A351** (1994) 111;
W.W. Armstrong *et.al.* (ATLAS Collaboration), *CERN/LHCC/94-43* (1994) ;
S. Amato *et.al.* (LHCb Collaboration), *CERN/LHCC/98-4* (1998) .

[6] Y. Grossman, Z. Ligeti and E. Nardi, *Phys. Rev.* **D55** (1997) 2768;
D. Guetta and E. Nardi, *Phys. Rev.* **D58** (1998) 012001.

[7] T. Inami and C. S. Lim, *Prog. Theor. Phys.* **65** (1981) 297 [*Err.* **65** (1981) 1772].

[8] PDG Collaboration, *Euro. Phys. Jour.* **C15** (2000) 1.

[9] S. Hashimoto, *Nucl. Phys.Proc.Suppl.* **B83** (2000) 3.

[10] See for example: A. Ali and D. London, *Euro. Phys. Jour.* **C9** (1999) 687.

[11] G Buchalla and A. J. Buras, *Nucl. Phys.* **B400** (1993) 225;
M. Misiak and J. Urban, *Phys. Lett.* **B451** (1999) 161.

[12] F. Abe *et.al.* (CDF Collaboration), *Phys. Rev.* **D57** (1998) R3811.

[13] S. Fukae, T. Morozumi, C.S. Kim and T. Yoshikawa, *Phys. Rev.* **D59** (1999) 074013;
S. Fukae, C.S. Kim and T. Yoshikawa, *Phys. Rev.* **D61** (1999) 074015;
S. Fukae, C.S. Kim and T. Yoshikawa, *Int. Jour. Mod. Phys.* **A16** (2001) 1703.